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Enabling exploration through automated manufacture

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Abstract

Automated manufacturing has the capacity to reduce costs for space exploration, enable initial technology exploration and further improvement of technological capabilities. Current manufacturing techniques can be adapted to create simple nanosatellites (e.g. CubeSats). Early automated manufacturing efforts with nanosats will provide important experience and techniques, paving the way for additional capabilities. Future manufacturing will allow more complex systems and modification to the base design prior to fabrication. These future systems may be needed on an ad hoc basis, to satisfy then-current exploratory needs, to explore a target of opportunity, and/or to recover after a failure or disaster. A path to the first automated manufacture of nanosatellites will be illustrated.

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1. Introduction

Future space exploration will see drones and robots as key assistants and primary explorers. One of the mundane, but critical, responsibilities will be on site automated construction from parts to fully operational machines. The ability of a machine to build another functioning machine from raw materials is still something of science fiction. But like most science fiction, the seeds of the technology are already available for automated manufacturing. Cars are constructed mostly or in part by robots, milling machines cut very accurate parts from steel blocks with astonishing speed, and computing capability has dramatically increased in the last 10 years. There are even machines for production of parts at home, such as the RepRap. All of these are precursors to automated construction. But the task is still difficult as material properties and degrees of freedom magnify even the smallest oversight.

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Since this technology will be difficult to develop initially, it makes sense to select a simple machine class that can be developed and tested inexpensively compared to current practice. One of the simplest machines being used to explore, categorize, and develop for space are nanosatellites, also commonly referred to as "CubeSats". Nanosats (for short) can provide a simple machine construct while learning how to automate manufacturing. Nanosats can be then made more complicated and larger satellites created as the manufacturing technology improves. Eventually the technology could allow a machine to generate, in situ on the moon, not only a dwelling for astronauts, but the robotic assistants they will need to maintain the facility. While currently science fiction, this isn't a far-fetched idea.

2. Business Case for Automated Manufacturing

For any endeavor to be pursued, a case must be made for the technology or product to generate value of some type. A business case for the use of automated manufacturing must exist for it to be a major part of space exploration. As the rest of this paper details, several advantages do exist. Automated manufacturing requires modularity, which leads to a greater ability to manufacture and to repair malfunctioning systems, potentially at a fraction of the cost of junking the satellite or accepting additional risk in operation by switching to the backup system. Using modular systems in automated manufacture can, with careful design, have a higher mass to volume (*i.e*. part density) than finished systems, which has benefits beyond manufacturing. Modular parts can be packed tightly in a smaller volume for launch. Reduction in volume can allow for a smaller, lighter fairing during launch. Production in orbit reduces the need for the entire system to be vibration tested. Raw materials do not need extensive vibration damping, and electronics can be packed densely in vibration reducing enclosures- both benefits are unachievable when launching a completed satellite. Once automated production in space is achievable, the size of an antenna, mirror, or space craft will no longer depend on the largest fairing diameter of the chosen rocket. This has the potential to drastically improve the reliability and efficiency of deep space observation. In the end, the reduction in lifting mass for fairings and the lack of vibration testing might provide enough savings for a business case to be made. Improved efficiency through additional collection capability might make otherwise impossible science and exploratory missions commonplace. Ability to repair through modular parts and digital schematics would provide risk reduction on multi-billion dollar satellites. These are three quick business cases, each capable of justifying automated manufacturing.

All of these scenarios provide ample evidence of a business case for the developed technology. Unfortunately, modern investment also requires a business case for building the first of its kind. What can the first automated construction in space provide that isn't already provided? Unfortunately, the first systems probably won't provide much over current production. The business case for the first iterations of the technology must be based on the fruit of the technology tree and not the initial seed. In the end, the easiest business case for the first automated manufacture is not because it itself is profitable, but represents exploration in a true sense, with the promise of savings and capabilities otherwise unattainable now.

There are multiple future uses for automated manufacturing technology that provide additional justification for pursuing this technology. Creation of mining robots to expand a mine or replace robot losses would ensure a consistent supply of workers in a hazardous environment near the point of use. Using robots and drones to construct the necessary structures and machines for colonization can prepare areas prior to human arrival, improving the efficiency of the colonization effort. Automated manufacture of goods in a space environment might be an economically viable method for some products. The use of similar technologies on earth might improve the yield of farmland, reduce the costs of manufacture of complex goods, and even streamline things as varied as house construction to scientific exploration. The capability to manufacture in an automated fashion, like other advances in technology, have basis in today's manufacturing.

3. Manufacturing Capabilities in brief

Semi-automated manufacture takes many guises today. Many products used throughout the world are made, constructed and/or packaged in an automated fashion. Household goods, toys, electronics are some examples of partial or fully automated manufacturing. Unfortunately, there is little in common between a toy robot and a satellite. Automated manufacture is not commonplace in aerospace applications, partially due to the single use systems built for a specific mission and the rocket it is launched on. A better way is possible utilizing automated manufacturing, and the methods that can be employed in aerospace applications are available in some existing manufacturing methods. Several areas that are applicable follow in a brief fashion, highlighting some of the relevant technologies currently in use.

Most automobiles have had parts installed, manufactured, or welded by large robots. Automotive manufacturing robots have been in use for at least the last 30 years. Today's advanced robots allow a vehicle factory to run with only a dozen or so employees on site. However, automotive robots are large, securely mounted in high-strength concrete, and singular in purpose. Their size is mostly due to the large mass of steel they might be maneuvering, but also the controls and hydraulics to automate the robot. These robots are limited in their accuracy within a certain tolerance required for automotive manufacture, which would not be acceptable for space-based applications. Precision for aerospace applications can be accomplished in each robot's actions, but the machines will require more expensive components. Some of these components might be available from the area of highly accurate electronics manufacture.

The construction of computer processors, motherboards, and electronics has been done by automated machines for several years. The machines pull from existing trays of parts (*e.g.* capacitors, resistors), spools of wire, and other integrated circuits. These robots maneuver the parts and place them accurately, within hundredths of a millimeter, of their assigned location on the board and solder each part in place. Processors require much tighter tolerances as some connections approach a nanometer in size. This would be a ridiculous level of accuracy for a nanosat, but the technology for extremely accurate motion is there. Those same electronics allow calculations on a scale previously only available with several rooms of circuitry and significant cooling. While the computing power of a modern processor would not be necessary for a nanosat, it will most likely be required for automated manufacture of the nanosat.

Automated milling and shaping has become quick and precise. Milling machines can automatically change tools and blanks, mill an aluminum block in excess of a thousand inches per minute while maintaining micrometer accuracy, and/or make the proper grinding tool from a standard blank prior to grinding. These machines are large and are intended for mass production of large items. Their underlying technology, however, was unheard of even ten years ago. These advanced milling machines are currently in use in aerospace applications in creating aluminum and titanium structures for aircraft. Mechanical cousins wind carbon fiber around fuselages and complex structures with the accuracy to create reliable composites for commercial use. The common theme of all of these machines is the replacement of manual labor for cost, expediency, accuracy, and, sometimes primarily, safety.

The use of sensors to control the manufacturing process is necessary for the proper manufacture of a nanosat. Microelectromechanical systems (MEMS) have revolutionized the types and capabilities of sensors. These small sensors are used for a wide array of uses, from safe airbags to entertainment within the Wii controllers. MEMS would be very useful in areas where the manufacturing has little space for a sensor, requires duplicate sensors, and as sensors for the nanosat. The ability to manufacture in an automated way will depend on the accuracy and reliability of sensors.

Each of these developments was not done overnight, and required a learning curve. Starting on simple structures paves the way for more complex methods and understanding. The current state of the art does display a capacity to do some amazing things manufacturing parts and some assembly. Combining related technologies to create the capacity for complex automated manufacture is the crux of the necessary technology tree. This base technology will ultimately aid space exploration and mastery more than even the most expansive science fiction has postulated.

4. Starting Point

The above examples of current manufacturing means are not a blueprint to automated manufacture. A conceptual method follows as a possible approach to automated manufacturing. This will blend different techniques and approaches to manufacturing to simplify the initial process so the focus is on learning how to automate manufacturing. It is important to note that the design of a nanosat that can be easily manufactured through automation also requires thought and design of the machine to create the nanosat. These two items can be designed together for the initial building process. However, as the technology improves, the machines will define the products that they are capable of producing, similar to many machines used today. It might be advantageous to use a similar approach initially, realizing that it will be an iterative process.

Some underlying needs exist within the nanosat design. The part count should be smallest possible, design the production system to minimize manufacturing motion, and use modular design principles. This keeps the manufacturing machine as uncomplicated as possible and reduces the likelihood of an error in construction. The design should be digitally defined so changes can be transmitted to the machine easily and accurately. Keeping with a simple product design ensures the initial necessary design features for in situ production- minimum power consumption and low required part count supply. Part and connection standardization coupled with modularization will define the design of the nanosat. The lower part count and minimum motion will help define the manufacturing machine. Nanosat design use of pre-made components is initially required, and should be designed to aid the machine in managing those parts. These parts of all types should be retained in appropriate systems for managed use during the manufacturing process.

Managing the process is the automated manufacturing machine itself. It must satisfy all of the required motions to construct the nanosat as well as maintain its functions. It will need to keep tally of parts, the locations of the mechanisms for manipulation, current status of the manipulators as well as future states, and deconflict the differing actions. Simply building a nanosat structure will require the maneuvering of structural members without collision of parts or machine, placing and mounting necessary parts, then rotating the structure accurately enough to allow for additional structural members to be attached. A simple nanosat should not be hard to deconflict, with more complex systems requiring more prediction and tracking. Simple motions can become quite complex computationally, requiring a robust processing capability even for the simpler machines. However, even construction of a complex machine uses the same base formulations, limiting the overall impact. This impact will be most keen on the first few nanosat production lines, so care must be taken in the initial stages.

As with all construction efforts, the automated manufacturing machine will need to discover, track and handle errors in a useful way. These errors include errors in construction, failed parts for construction, and errors within the automated machine. Once something has been discovered to be incorrect in the construction, the machine will need to correct the failure. An ability to “call home” will be necessary for unpredicted errors. A method of discharging an unusable build will also need to be available to the manufacturing machine if a detected failure is not a correctable one. Once the machine is capable of handling, tracking, basic error control and manipulating parts and complexes, the first nanosats can be attempted.

Starting the nanosat manufacturing process is the creation of the multiple parts to construct the nanosat. These parts include, but not limited to, structural members, solar cells, electronic controllers, and batteries certified for space flight. Parts will be constructed prior to running the automated manufacturing process for the initial uses of the technology. This ensures the capability being developed and tested is automated manufacturing. Commercial solar cells will need to be reinforced as the panels will encounter stresses in the manufacturing process that could damage the solar cell. Electrical control boards should be tested to ensure the operation of the board prior to installation on the nanosat. This should be done by the automated manufacturing machine prior to installation of the part. Batteries for the nanosat might be initially cheaper to be purchased off the shelf and require modification for nanosat use before being included as a construction part. Each of these pieces can be built using automated processes as the experience in automated manufacture increases.

Structural members can be easily made using multiple different approaches. The simplest is to manufacture the members from a ductile material, such as sheet aluminum or moldable plastic with a UV cure. A computer aided manufacturing (CAM) system can machine the cross members and necessary sheet plates. A roller assembly can create folded members cut to length and any necessary holes. Part of the structural considerations is how to connect each of the components together. Contact, or cold, welding is a low power, reliable method of joining parts in a space environment (*i.e*. a vacuum). Contact welding looks to be the best method for the initial technology, but other methods might also be relevant, like rivets. Rivets are a tried and true method of attaching parts together. Rivets might be one of the simplest methods as it requires only placement and a linear motion to finish. Other methods of welding and securing items can be included as automated manufacturing technology permits.

In order to best incorporate the understanding of all the implications of using automated manufacturing, sensors and programming should replicate all functions, including part availability sensing. Once the sensors indicate the necessary parts are available in sufficient quantity, manufacturing can begin. The parts can be grabbed with multiple means, including electromagnets, rollers, or gripping implements (*e.g*. pinchers). Regardless of the means used to manipulate the part, the position of the part must be precisely controlled to ensure no collisions and proper placement. This most likely will require six degrees of freedom understanding of the part and the system manipulating the part to prevent over travel and unwanted stress or deformations. Each part should be moved to its construction berth and mounted in some temporary method to firmly fix the part's location. Sensors can keep positive track on the temporarily fixed part and its status, and note when the part has been fastened.

As the structural members are placed, the parts can be fixed to each other using the chosen method. Non-structural parts designated for that portion of the nanosat, such as solar panels, can then be placed and mounted. Usually this will result in further stiffening and possibly twisting of the section and should be detected by the system. As production continues, the partial nanosat structure will need manipulation into a new position to allow other parts to be attached. Sensors will be needed to ensure the partial structure is moved to the proper location and locked to prevent collisions between the partial nanosat, its components, and the manufacturing machine. Once the structure is locked in the new position, construction can resume. This process may be repeated several times during construction, depending on the design of the nanosat.

The electrical connections represent a manufacturing challenge. Standard connections require dealing with wires and possibly sockets. Instead of using flexible wires for the power connections, aligned pin systems would achieve the same purpose with little additional complexity. The pins will most likely need to be secured, and use of the fastening method should be applied to connect the electrical components. Fasteners, if used, must be sufficiently conductive and be the standard fastener used throughout the system. Either way, a connection method must provide a secure means that utilizes an existing part and method of manufacture to create a near-permanent electrical connection.

5. Developing the Technology Tree

Every technology tree starts with the first incarnation, and quickly grows as the technology evolves, as new uses are created, and techniques are developed. Production of a simple nanosat is an easier implementation of the initial technology in an area that would benefit over current manufacturing. The core of this technology is the capability to dynamically control the components during construction of a complex machine. Initially this process will be static and piecemeal, followed by a more fluid process with improved controls and process. It should be expected that early nanosat construction will be slow, methodical, and result in non-working nanosats. Iterations will follow and ultimately result in a base design for automated manufacture as well as the initial automatically manufactured nanosat prototypes.

These first complete nanosats would never make it to orbit. They would be tested and run through diagnostics to ascertain the quality of work over several satellites. Once the quality is proven, several nanosats would be constructed to do the same functions. These would then be launched into space and tested. Additional testing of nanosats with small variations, possibly in programming or attached sensors, would be undertaken to expand the working knowledge of the technology. As the available sensors and technologies expand, the costs for automated production would steadily decrease. The reduction in costs for production and increased capability will naturally lead to more complex systems. As the complexity increases, automated manufacture will begin constructing elements of larger satellites leading to construction of satellites. When communication satellites are being designed for production by automated means, the technology should be prepared for the unknown challenges of production in situ and for space exploration.

In situ automated manufacture becomes more complex because of the desire to minimize interaction and the necessary resources that must be replenished. Initially, replenishment will entail most of the needs with little capitalization of in situ raw resources on planetary bodies. Specialized items, like electrical components, might take longer to be able to manufacture in situ, requiring replenishment until the in situ technology exists. Initial construction of structures and machines using large shipments of bulk items will be required no matter the location of the automated machine. Replenishment using optimized payloads would enable a stellar version of “just in time” manufacturing by providing the parts just before needed in construction, based on the detailed designs being implemented by the manufacturing machine.

For space based in situ construction, mass shipments of refined raw materials provide an economy of scale in the efficiency of transport of raw materials. A large roll of sheet aluminum is massive, but vibrations of space launch won’t harm the material. Likewise shipments of electronics and solar panels can be made in a dense, vibration resistant manner because these will be unpacked and made into useful, less compact systems later. This enables a more versatile launch and construction capability. Dense packaging reduces the need for large fairings and extensive vibration testing of complete structures. The downside of space based in situ is the lack of immediate localized resources. However, this can be mitigated through the use of replenishment from off-Earth locations.

Planetary body in situ should shift, over time, to the use of any relevant local resources for construction. This requires continued replenishment for any materials not found in the environment as well as a method to mine and refine the materials that are available. Automated manufacture from the resources to exploit the local environment provides a return on the initial resources as the local sources are increasingly improved and exploited. The same method used to send resources to the site could be used to send the local excess back to Earth or other locations.

When the bulk shipment arrives, the in situ system can unpack the shipment as appropriate. As local resources become available, the input of these resources changes but the manufacturing process after that point does not. Upon receiving the designs and instructions, the automated manufacture begins and continues until all of the designs are made, or the required materials run out. Some level of resource depletion will be normal until the peculiarities of each location are well understood.

Automated manufacturing negates a risk currently inherent in space travel- critical machines that break are not repairable and hamper the mission. An initial path to achieve success might be to create another machine suitable to replace the failed machine with very little wait time. If repair capability has been developed by this time, it can be tried first. Due to the digital designs, automated manufacturing machines should entail some level of repair capability. However, the automated manufacturing machine will need to be instructed on how to repair the broken machine, which will most likely require some specialized approaches. If a need arises for a modification to a new, or existing, structure or machine, it would then be straight forward to use repair and construction modes. Allowing variations of machines enables alterations in the missions to be more adaptable to the changing, current situation.

Taking advantage of an opportunity, such as a small drone or nanosat to investigate a new crater, would be possible and cause a limited, if any, disruption of the current mission. The in situ machine would simply generate a drone, give it directions and let it go. The drone would do its investigation and either be directed to a new site or recycled into parts. Moreover, the loss of the same drone would not cost the mission an irreplaceable machine. Another could be constructed, assuming the parts are available.

The same concept could be used to recover a mission when a system or machine fails. A failure of a machine on a colony on Mars can be fatal before a replacement from Earth is even loaded onto a proper rocket stack. In situ manufacturing might be the only realistic way of reducing risk and ensuring mission success. Another example would be the loss of an antenna on a deep space probe, or even an Earth orbiting communications satellite. If there is the potential to repair a hardware failure, the mission can have a reduced level of risk and save potentially millions of dollars per repair.

These simple extensions of the technology show the potential of the manufacture at near the point of use. It also displays variations of the tree: complex systems, non-moving structures, purpose built robots, modular repair, on-the-fly reconfiguration, and part recycling. Extension of these branches eventually leads to additional capabilities that can be added in new places. For an example, space probes might gain from this technology by carrying a limited capacity to manufacture. If a target of opportunity arises, a probe can generate the necessary sensor and transmitter to do a short, targeted investigation. This would be akin to the Hayabusa probe being able to generate a new lander to replace the one that was lost. Alternately, it could have released a different sensor package custom made for the environment to report from the surface of the asteroid. Another option would be for a deep space probe to release smaller probes as it passes the moons of Jupiter or the rings for further evaluation while the main probe continues on its path. This adds a small amount of complexity and flexibility to a future space probe, but can reduce the mission risk and greatly increase the knowledge learned from a single probe. This expands the possible mission profiles and capabilities with limited risk and cost.

There are clear uses of complex automated manufacturing, and all of the possibilities won't be known beforehand. However, the first steps need to be taken in the form of lowly, fairly simple machines that can be constructed automatically. Nanosats can establish complex automated manufacturing as a viable aerospace technology in a relatively short time frame. After that, human ingenuity will drive new uses for the manufacturing process to serve the needs of space exploration and colonization.

6. Conclusion

The advantage of automated manufacturing is clear. Construction of complex machines through automation reduces manufacturing costs, reduce the risk of exploration, and improve the chances of successful missions to space. Automating manufacture is not yet possible, but the seeds are all available. By automating the manufacture of a simple nanosat to proof the technology, first on Earth and eventually in space, the lessons necessary to success can be learned at an affordable price. These small satellites will usher in a whole new method of construction, one that is alluded to in space colonization papers and science fiction but never truly defined. This paper has shown, conceptually, that this technology can be a reality soon, and enable a myriad of capabilities in time for their use in exploring our solar system.